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ABSTRACT

The concept of truck platooning has been the focus of many research projects over the years at the California PATH Program and around the world through such projects as CHAUFFEUR, SARTRE, KONVOI, Energy ITS, and COMPANION. These previous projects have included the automation of both lateral and longitudinal control in the following trucks because of the very close following distances targeted by those projects. Cooperative Adaptive Cruise Control (CACC) provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors.

There are important distinctions between CACC and automated truck platooning. First, with CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, while truck platooning systems have relied on a Constant Distance Gap (CDG) control strategy, CACC has relied on a Constant-Time Gap (CTG) control strategy, where the distance between vehicles is proportional to the speed. For these reasons, a series of trucks using CACC is referred to as a string, rather than a platoon.

This report mainly focuses on describing the various CACC operational concept alternatives at the level of individual vehicles, local groups of vehicles and their drivers, and which alternatives should be employed in this research project. These operational concepts can be broken into four categories: string formation, steady-state cruising, string split maneuvers, and faults or abnormal operating conditions.

Key Words: Cooperative Adaptive Cruise Control, CACC, Adaptive Cruise Control, ACC, Intelligent Transportation Systems, ITS, Speed Control, Truck Platooning, V2V Communication, DSRC

EXECUTIVE SUMMARY

Project Overview

This report discusses the operating concept alternatives for truck platooning using Cooperative Adaptive Cruise Control (CACC). It is part of a series of reports being produced by the California PATH Program, funded through the Federal Highway Administration's (FHWA) Exploratory Advanced Research Program (EARP) and Caltrans. The project team includes PATH, Volvo Technology of America, LA Metro, the Gateway Cities COG, and Cambridge Systematics, Inc. The goals of the project include identifying the market needs for a CACC based truck platooning system; building, demonstrating, and testing a CACC system on commercial trucks; and evaluating the potential benefits of CACC along the I-710 corridor in California.

The concept of truck platooning has been the focus of many research projects over the years at the California PATH Program and around the world through such projects as CHAUFFEUR, SARTRE, KONVOI, Energy ITS, and COMPANION. At highway speeds, fuel consumption is significantly influenced by air resistance, and the shorter following gaps can significantly impact fuel economy for large trucks, with energy savings potentially as high as 20% to 25%. However, most truck platooning projects have emphasized a very close coupling between vehicles, maintaining a constant distance from one vehicle to the next. The prior PATH truck platooning studies tested gaps between trucks as small as 3 m to 6 m. Following gaps this short are likely to require the implementation of dedicated truck lanes and automation of both speed control and automated steering on the trucks. The dedicated lanes would be required for safety because trucks following at such close distances will leave very little opportunity for other traffic to change lanes across the platoons, and the platoons will have a hard time responding safely to emergency conditions created by bad behaviors of other vehicles' drivers. Automated steering will be required because driver forward vision will be highly limited at such short following gaps.

Limited vehicle speed automation has already been commercially deployed in some trucks using Adaptive Cruise Control (ACC) systems, but the performance of these systems is limited to much longer following time gaps than would be required for truck platooning. However, in the near term, CACC provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. CACC systems build upon the current ACC system by adding V2V communication to supplement forward-looking sensors. Adding communication reduces sensor processing delays, enabling shorter following gaps while reducing string instability.

However, even though CACC is a potential next step towards truck platooning, the term has been used loosely in recent years and there are important distinctions to be made between CACC systems and automated truck platooning systems. First, with CACC, only truck speed control will be automated. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, truck platooning systems have relied on a Constant Distance Gap (CDG) control strategy, where the separate between vehicles remains unchanged with speed. The CACC control strategy is based on a Constant-Time Gap (CTG), where the distance between vehicles is proportional to the speed. Previous CACC studies at PATH have shown that following time gaps in the range of 0.6 s at 65 mph (roughly 17.5 m gap) were acceptable for drivers of passenger vehicles. These much larger following distances were more comfortable for drivers, while still allowing the surrounding traffic enough room to merge across a string of CACC vehicles when necessary. For these reasons, a series of trucks using CACC is referred to as a string, rather than a platoon.

The bulk of this report focuses on discussing the CACC operational concept alternatives and making recommendations for this project regarding how the CACC system should function at the level of individual vehicles and local groups of vehicles. The operational concepts can be broken into four categories: string formation, steady-state cruising, string split maneuvers, and faults or abnormal operating conditions.

CACC String Formation

CACC operation starts with string formation. From the driver and system perspective, one or more truck drivers will activate the C/ACC system and set their desired speed and gap setting. Drivers may also pre-set a preference for leader or follower to be used when forming a new string. Once the C/ACC system is active in ACC mode, the CACC local coordination feature will search for additional trucks (or existing strings) within communication range with which to couple. The joining driver will then be displayed a list of nearby trucks or existing strings with which coupling is possible, taking into consideration any driver pre-set preference for the leader or follower position. The DVI may display a list, a simple graphical representation of the relative vehicle positions, or if the vehicles are separated by some distance, a map display depicting the relative positions.

Once a joining truck driver selects a lead truck (or existing string) to couple with, the local coordination feature will confirm with the lead truck and instruct the lead truck (or string) to slow down, while instructing the joining truck (or string) to speed up. The lead driver of the string and the driver of the truck wishing to join the string will each be displayed a target speed and target lane in which to travel during the coordination. Additionally, the target speed during the coordination maneuver will automatically be set as the C/ACC set speed. In addition to the target coordination speed, the DVI will also need to display the relative location, relative lane, distance, and if necessary, an indication of when the joining truck driver should change lanes to get behind the lead truck (or string).

Once the joining truck is directly behind the lead truck (or existing string), the CACC system's vehicle following mode will engage automatically, and the lead truck's former set speed will be restored and relayed to all of the following trucks. Once in the string, the drivers will be able to select any of the available CACC following gaps.

CACC Steady-State Cruising

Steady-state cruising is what truck drivers will be doing most of the time while the CACC system is engaged. Once a string is formed, the drivers will still be tasked with actively steering their vehicles and monitoring vehicle status and traffic conditions, but steady-state cruising should only be interrupted when trucks join into or split from the string or when an unequipped vehicle cuts in between the following trucks in the string. Because cut-ins in on-the-road testing will be unavoidable, the CACC system needs to be designed to automatically handle a cut-in by splitting the string and commanding the new lead truck, directly behind the cut-in, to fall back to a longer ACC gap setting and following strategy. Once the unequipped vehicle departs the lane, the CACC system can automatically re-join the two split strings and close the gap. The driver will still be responsible for monitoring for potential cut-ins and disengaging the CACC system through manual braking should the system fail to respond appropriately.

CACC String Split Maneuver

Any truck in the CACC string may depart the string at any time, and the effect that the departure will have on the string will depend on which truck is exiting the string. In an ideal departure, the driver of the departing truck will signal their intent to exit the string by activating the turn signal or otherwise indicating so on the DVI. If a driver signals their intent to depart, then any following drivers in the string will be notified of the maneuver through their DVI. In the least disruptive case, the departing truck simply changes lanes, and the following trucks close the gap. However, in some case, the departing truck may need to revert to manual speed control before changing lanes. In the case when the departing truck is a middle truck in the CACC string, the string will need to be temporarily split into two strings, with the departing truck leading the second CACC string under manual control until it fully departs the lane. Once the departing truck changes lanes, the trucks that were following it will rejoin the original CACC string and close the gap left by the departing truck.

CACC Fault Conditions

The design of the CACC system will need to consider a number of potential faults, errors, and abnormal operating conditions. The first issue that must be considered is what happens when the CACC system is disengaged. No matter how the system is disengaged, it is critical that the DSRC broadcasts continue because the other trucks in the string will be relying on those transmissions. Furthermore, a research system will require a kill switch, and the design of the kill switch should ensure that the DSRC broadcasts continue and that some indication of the kill switch status is included in the broadcast transmission. If the kill switch is tripped, the following trucks need to know not to pay attention to any vehicle commands still being broadcast by the CACC system.

Other fault conditions that must be considered include a data mismatch between the forward sensor data and DSRC message contents and DSRC signal drops or missed messages. Both of these conditions may happen during normal operation of the vehicles, and in both cases, the strategy is simply to rely on the forward sensor and slowly back off the following distance to a following time gap more appropriate for ACC operation.

Finally, the CACC system must consider how to handle unexpected road hazards, such as a stopped vehicle or debris in the travel lane, and any resulting hard braking or emergency stop maneuvers. One of the challenges with CACC for trucks stems from the fact that the following truck drivers will have limited forward vision, and this places some additional responsibility on the driver of the lead truck in the CACC string. If there is a stopped car or obstruction in the roadway, the lead truck cannot simply change lanes to avoid the hazard because doing so will surprise the following trucks' drivers, and the following truck drivers may not have enough time to act appropriately.

In the long term, a CACC system for trucks will need to incorporate some ability for the lead truck driver to send instructions (lane changes) or warnings (road hazards) to the following trucks, but for this project, a safety observer and radio operator will be in the lead truck to verbally communicate any hazards to the following truck drivers. As for the emergency braking scenario, operational considerations will depend on the braking authority granted to the CACC system. If the CACC system is not capable of bringing the vehicles to a stop in a hard braking situation the driver must be warned, reengaged in the speed control, and required to take over braking.

Summary and Conclusions

While the concept of closely-coupled truck platooning has been the focus of many research projects over the years, it has always included the automation of both lateral and longitudinal control in the following trucks because of the very close following distances targeted by those projects. CACC provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. There are important distinctions between CACC and automated truck platooning. First, with CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, while truck platooning systems have relied on a Constant Distance Gap (CDG) control strategy, CACC has relied on a Constant-Time Gap (CTG) control strategy, where the distance between vehicles is proportional to the speed. For these reasons, a series of trucks using CACC are referred to as a string, rather than a platoon.

This report mainly focused on describing the CACC operational concept alternatives, and which alternatives should be employed in this research project. The operational concepts can be broken into four categories: string formation, steady-state cruising, string split maneuvers, and faults or abnormal operating conditions. With CACC string formation, the options included *ad hoc*, local, and global coordination strategies as a means to help the CACC equipped truck drivers find each other, especially at low market penetrations. Both *ad hoc* and local coordination are appropriate for this project, but global coordination, which includes routing the trucks on city streets, is beyond the scope of this project. The primary issue with steady-state cruising is effectively dealing with cut-ins, which will result in a temporary string split maneuver.

Finally, a number of fault conditions and emergency maneuvers were considered including communication failures, the design of a kill switch (used in research only), and how to handle obstacles in the roadway and hard braking situations. For the most part, system states, fault conditions, and emergency kill switches must be designed to keep the DSRC broadcast active while attempting to clearly indicate what is happening with the truck since any following trucks will be relying on those transmissions. As an example, if the kill switch is activated, the DSRC broadcast should indicate that the data provided regarding CACC vehicle commands cannot be trusted. Furthermore, in the longer term, the role of the CACC string's lead truck driver must be clearly defined, and the CACC systems will need to incorporate some ability for the lead truck driver to send instructions (lane change) or warnings (road hazards) to the following trucks.

ACRONYMS

ACC	Adaptive Cruise Control
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
C/ACC	Cooperative and/or Adaptive Cruise Control
Caltrans	California Department of Transportation
CDG	Constant Distance Gap
COMPANION	COoperative dynamic forMation of Platoons for sAfe and eNergy-optimized gOods transportatioN
CTG	Constant Time Gap
DSRC	Dedicated Short Range Communication
DVI	Driver-Vehicle Interface
EARP	Exploratory Advanced Research Program
FHWA	Federal Highway Administration
FCMBS	Forward Collision Mitigation Braking System
FCW	Forward Collision Warning
GCDC	Grand Cooperative Driving Challenge
GPS	Global Positioning System
ITS	Intelligent Transportation Systems
I2V	Infrastructure to Vehicle (communication)
NAHSC	National Automated Highway Systems Consortium
NHTSA	National Highway Transportation Safety Administration
PATH	Partners for Advanced Transportation tecHnology
SAE	Society of Automotive Engineers International
SARTRE	SAfe Road Trains for the Environment
V2V	Vehicle to Vehicle (communication)

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1 INTRODUCTION

1.1 Project Overview

This report is part of a series of reports on Cooperative Adaptive Cruise Control (CACC) and truck platooning that are being produced by the California PATH Program, funded through the Federal Highway Administration's (FHWA) Exploratory Advanced Research Program (EARP) and Caltrans. The project team includes PATH, Volvo Technology of America, LA Metro, the Gateway Cities COG, and Cambridge Systematics, Inc. The project team will assess the market needs for partially automated truck platoon systems in the local drayage and long-haul trucking industries and explore how the truck platoons could contribute toward improving the traffic flow and environmental mitigation for the I-710 corridor, with its very heavy truck traffic. PATH and Volvo will develop a new generation CACC system for three Class-8 tractor-trailer trucks, building on the existing Adaptive Cruise Control (ACC) system that Volvo already has in production, and will test it to determine performance and driver acceptability. Systematic tests will determine driver preferences for truck-following gap, and then the preferred gap settings will be tested to provide careful measurements of the energy savings that can be achieved from aerodynamic drafting of the trucks. The project will conclude with public demonstrations of the truck platoon system in the Los Angeles-Long Beach port area and in the Washington DC area.

1.2 CACC and Truck Platooning Background

The concept of truck platooning has been the focus of many research projects over the years both at the California PATH Program and around the world through such projects as CHAUFFEUR, SARTRE, KONVOI, Energy ITS, and COMPANION. Automated speed control in freight truck operations promises shorter gaps between trucks, leading to reduced traffic congestion and improved fuel efficiency. At highway speeds, fuel consumption is significantly influenced by air resistance, and the shorter following gaps can significantly impact fuel economy for large trucks with energy savings potentially as high as 20% to 25% (California PATH, Browand, et al., 2004; Shladover, et al., 2011; Lu and Shladover, 2011; Scania and the Swedish Research Council, Alam, Gattami, and Johansson, 2010; the Energy ITS project, Tsugawa, et al., 2011; and the SARTRE project, Dávila, 2013a). The fuel savings alone will result in dramatic operating cost savings for truck fleets and significantly reduce U.S. dependence on petroleum for transportation.

Truck platooning research has always relied on some form of Vehicle-To-Vehicle (V2V) communication to help compensate for sensor delays inherent in radars and lidars, and most automated vehicle control projects discussing platooning have emphasized a very close coupling between vehicles in order to maintain a constant distance from one vehicle to the next. The prior PATH truck platooning studies tested gaps between trucks as small as 3 to 6 m with fuel savings as high as 14.5% when following at 6 m. However, following gaps this short are likely to require the implementation of dedicated truck lanes and automation of both speed control and steering on the trucks. Dedicated lanes enhance safety because trucks following at such close distances will leave very little opportunity for other traffic to change lanes across the platoons and will have a hard time responding safely to emergency conditions created by bad behaviors of other vehicles' drivers, and automated steering will be required because drivers' forward vision will be highly limited at such short following gaps. Manual steering with no visibility of the forward road will result in a higher workload for the driver, increasing the onset of fatigue, and lateral offsets between trucks arising from manual steering inaccuracy will create additional drag, reducing the potential fuel savings that could otherwise be achieved.

Cooperative Adaptive Cruise Control (CACC) is an intermediate step toward a longer-term vision of trucks operating in closely coupled automated platoons on both long-haul and short-haul freight corridors. With CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors, but the drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Additionally, rather than the very closely-coupled, constant-clearance-distance control strategy, CACC relies on a more loosely coupled, constant-time-gap following strategy whereby the distance between the trucks varies with speed. PATH CACC studies with passenger vehicles (Nowakowski, et al., 2010, and Milanés, et al., 2014) have considered following time gaps in the range of 0.6 s at 65 mph, equating to a 17.5 m gap between vehicles at highway speeds, without any lane keeping automation or assistance. Even with this short a following time gap, the surrounding traffic, although discouraged, was able to maneuver between followers to create cut-in scenarios. Because of the key differences in the drivers' roles and responsibilities and the vehicle speed control strategies, CACC should not be referred to as truck platooning. To highlight this difference, a group of CACC equipped vehicles is referred to as a CACC string, rather than as a platoon.

1.3 Project Goals and Report Overview

The overall goal of this project is to demonstrate that CACC will provide sufficient benefits to justify the investment because although the long-term vision of full truck automation in dedicated lanes cannot be reached in a single leap, truck CACC should prove be an important step towards that direction. The goal of this report, within the context of the overall project, is to examine the alternative operational concepts for managing the formation and operation of truck CACC strings, and then to define a specific operational concept for the CACC system that is to be designed, implemented, and tested in the subsequent phases of this project.

The concept of operations developed in this document is focused on a Level 1 truck automation system (longitudinal control only) at the level of an individual truck or a local group of interacting trucks and their drivers. It complements an earlier concept of operations that was developed for the I-710 freight corridor by the local agencies in that region.[1] The corridor concept of operations was much broader in scope and emphasized the local infrastructure development and operations issues, including policy considerations, to achieve the goals of reducing emissions while increasing throughput of the heavy truck traffic along I-710 by building 16 miles of physically-separated lanes for trucks that would be electrically propelled and automated to varying extents by 2025. That report identified the transportation needs specific to the I-710 corridor that could be satisfied, in part, by truck platooning, after considering the inputs of the local stakeholders, the physical constraints, and the policy

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[1] *Initial Concept of Operations for the I-710 Zero Emissions Freight ITS Corridor*, report by Cambridge Systematics Inc. for the Gateway Cities Council of Governments and Los Angeles County metropolitan Transportation Authority, 2013.

constraints. The corridor concept of operations document only described traffic management and enforcement issues and failure scenarios at the system level (incidents, evacuations, construction and maintenance activities). While it did include some lower-level operational scenarios, those scenarios were largely based on ill-supported technological assumptions that may need to be reconsidered based on the results of this project.

The literature reviewed in Section 2 of this document reveals a wide variety of concepts for how to organize trucks within platoons, but much of the prior literature is based on fully automated truck platooning, rather than CACC, in which only the speed control is automated and drivers retain responsibility for steering control. The literature also reveals that CACC has been used to describe multiple concepts and is often used interchangeably with truck platooning. This report reviews prior CACC and truck platooning concepts and discusses the difference between CACC and truck platooning. It then explores concepts for CACC string formation, including an examination of the implications of both passive and active coordination and clustering strategies, truck sequencing strategies, and strategies for performing the joining maneuver. It is likely that active coordination strategies will be needed to improve the economic viability of CACC string formation at low market penetrations, and the impact of these strategies on the operating concept has not yet been fully explored.

Similarly, this report explores the issues associated with departing or splitting up the string, along with other likely scenarios that will be encountered during CACC cruising, such as cut-ins by unequipped vehicles and limited fault conditions. To round out the discussion, the CACC string operating concepts must consider electronically managing the economic transfers among the trucks that are clustered together within a string because the lead truck saves the least energy and the middle trucks save the most energy, and CACC operations are likely to need such a transfer payment system to motivate as many users as possible to use CACC to gain its efficiency benefits.

2 CACC AND TRUCK PLATOONING LITERATURE REVIEW

2.1 System Definitions: CACC vs. Truck Platooning

Cooperative Adaptive Cruise Control (CACC) is a term that has been used loosely in recent years and is often mistakenly assumed to be synonymous with platooning (Shladover, Nowakowski, Lu, and Ferlis, 2015); however, there are important distinctions to be made between CACC systems and automated truck platooning systems. In fact, CACC has been used to describe multiple system concepts, each using the combination of automated speed control with a cooperative element, such as Vehicle-to-Vehicle (V2V) and/or Infrastructure-to-Vehicle (I2V) communication. The V2V communication provides information about the forward vehicle or vehicles, and the I2V communication provides information about traffic further ahead and about local speed recommendations as part of an active traffic management approach. CACC systems can be implemented with either or both I2V and V2V information sources.

Both CACC and truck platooning are subsets of the broader class of automatic vehicle speed control systems. However, CACC only provides longitudinal control, leaving the driver to remain responsible for active steering control and for the active monitoring of the driving environment. The concept of truck platooning has generally included a system capable of both lateral and longitudinal control. Thus, the first difference between CACC and truck platooning is that CACC only represents Level 1 automation on both the SAE (2014) and NHTSA (2014) scales of driving automation, while truck platooning would represent at least a Level 2 automation system (on both the SAE and NHTSA scales).

The second major difference between CACC and truck platooning can be found in the vehicle-following control strategy. Many vehicle-follower speed control strategies have been proposed over the years, based on a wide variety of feedback control approaches and applying data from different combinations of vehicles (Shladover, 1995), but it is not necessary to review all of the strategies in detail because only a few strategies have ever been implemented and tested.

Truck platooning projects typically have emphasized a very close coupling between vehicles employing a constant-clearance-distance car-following discipline. This discipline is also sometimes referred to as a constant distance gap (CDG) strategy, where the separation between vehicles remains constant and does not vary with vehicle speed. The tight control achieved using this strategy gives the perception of a mechanical linkage between the vehicles, but stability can only be achieved using communication to broadcast the behavior of the platoon leader to the rest of the vehicles in the platoon (Swaroop, Hedrick, Chien, and Ioannou, 1994). Interruptions in communication are also more serious using the CDG strategy, and with such short following distances between trucks, emergency braking maneuvers could potentially lead to low speed impacts among the followers, especially if different loading and braking performance characteristics between trucks are not factored in.

In contrast, both commercial ACC and CACC research projects have typically employed a constant-time-gap (CTG) vehicle following strategy, since this strategy more closely represents how humans normally drive at highway speeds. Using a CTG strategy, the distance between vehicles is proportional to their speed (plus a small fixed offset distance), so that a doubling of speed leads to an approximate doubling of the clearance or distance gap between the vehicles.

Note that following time gap is often erroneously described as “headway” or “time headway”, but headway has traditionally been defined as the time from front bumper to front bumper, whereas following time gap is defined as the time from the rear bumper of the preceding vehicle to the front bumper of the following vehicle.

As stated in the introduction of this paper, since CACC uses a CTG following strategy instead of a CDG following strategy and since CACC still requires drivers to actively steer the vehicle while monitoring roadway and traffic conditions, this paper refrains from referring to a sequence of CACC vehicles as a platoon, and instead, it refers to a sequence as a CACC string (Shladover, Nowakowski, Lu, and Ferlis, 2015).

2.2 *Ad Hoc*, Local, and Global Coordination Strategies

Forming CACC strings of trucks may require some form of coordination to aid the equipped trucks’ drivers in finding each other on the highway, especially at low market penetrations of V2V and CACC. A recent paper (Shladover, Nowakowski, Lu, and Ferlis, 2015) discussed three coordination options or strategies that have been described in the literature: *ad hoc*, local, and global coordination. The first strategy is *ad hoc* clustering, whereby CACC vehicles only couple if they happen to be following each other on the highway. Most of the existing studies of CACC in passenger vehicles have relied on ad-hoc clustering. An important point in *ad hoc* clustering is that the lead vehicle does not need CACC, only V2V communication, because the lead vehicle can be driven manually while the following vehicle uses CACC. Thus, the likelihood of finding a vehicle to couple with increases with the market penetration of V2V equipped vehicles, not just CACC vehicles, and there may be ways to help concentrate V2V equipped vehicles, such as through incentives or requirements in dedicated lanes, in order to facilitate a higher local concentration of CACC usage.

The second strategy, local coordination, attempts to actively match equipped vehicles to promote the formation of CACC strings. Equipped vehicles, or streams of vehicles, already on the highway and within a certain distance of each other, could be instructed to speed up or slow down to facilitate coupling. This approach was discussed in the SARTRE project (Chan, 2012) and in the predecessor work to the COMPANION project currently led by Scania (Liang, Mårtensson, and Johansson, 2013). The local coordination could use the V2V DSRC communications, but given the limited range of this medium, cellular or other longer range communication media may be necessary. Once nearby equipped vehicles are located, instructions would be provided to the drivers of one or both vehicles on how to locate each other, presumably by slowing down, speeding up, and/or changing lanes.

The final strategy, global coordination (Larson, Krammer, Liang, and Johannson, 2013, and Larson, Liang, and Johansson, 2014), attempts to match equipped vehicles through advanced pre-trip planning, matching vehicles by origin, destination, and estimated departure time. By adjusting departure times, routes, and vehicle speed while traveling on local streets, the equipped trucks can be coordinated to arrive simultaneously at highway entrance points and maximize the time spent travelling in a CACC string once the trucks have entered the highway.

2.3 Review of CACC Truck Platooning Operational Concepts

2.3.1 Overview

Truck platooning has been the focus of a number of research projects over the past 20 years including the European Commission's CHAUFFEUR and SARTRE projects, PATH's truck platooning projects in California, and the Energy ITS project in Japan. All of these truck platooning studies relied on CDG control strategies, rather than the CTG control strategies used in CACC. The topic of CACC has received somewhat less attention until more recently, and CACC system implementations to date have been limited to PATH in California, TNO (Netherlands Organization for Applied Scientific Research) and TU Eindhoven in the Netherlands, and several Japanese auto manufacturers who provided demonstrations at the ITS World Congress in Tokyo in 2013. Furthermore, all of the CACC research to date has focused on passenger vehicles, rather than heavy trucks. This section reviews the scope and some of the specific findings from each of the relevant projects pertaining to the concept of operations for truck platooning.

2.3.2 CHAUFFEUR

One of the first on-the-road demonstrations of truck platooning was accomplished in the European Commission's CHAUFFEUR and CHAUFFEUR2 projects (Benz, et al., 1996, and Fritz, Bonnet, Schiemenz, and Seeberger, 2004). These projects explored the concept of an "electronic tow-bar" system to couple trucks together on European roads. In the CHAUFFEUR concept's ideal system, the lead truck would be driven manually, and the following truck or trucks would be fully automated. The lead truck driver would then be fully responsible for the platoon, while the following truck drivers would have minimal capability for self-surveillance and emergency take-over in critical situations, consistent with the definition of an SAE J3016 Level 2 automation system for the leader and Level 4 for the followers. Although the CHAUFFEUR projects went into great detail on potential fault conditions and communications protocols during coupling, the project did not appear to go into any further details in conceptualizing operational strategies to specify where or how the coupling of trucks would occur in the real world or from the driver's perspective.

2.3.3 PATH Truck Platooning and Passenger Car CACC Research

Most of PATH's earlier research on automated platooning of trucks, buses, and passenger cars have been based on the long-term vision of the National Automated Highway Systems Consortium (NAHSC) program (1994-1997). This vision was based on the assumptions of fully-automated vehicle operation (SAE Level 4) within dedicated, protected lanes, from which non-automated vehicles would be excluded. Although the target vision of the NAHSC was based on SAE Level 4 freeway driving, the systems that were built and demonstrated operated at SAE Level 2 (continuously supervised by test drivers who were prepared to intervene at any time in case of faults). Transitions between driver control and automated control would occur at the entry and exit points of the dedicated lanes and the coordination of vehicle maneuvering, including platoon formation and dissolution, would be accomplished by computer controllers residing in the lead vehicle of each platoon or on the roadside at specific locations (entry or exit ramps or specific highway links). These types of operations are very different from the model of

CACC operations in mixed traffic conditions that we are focusing on in the current project, even though we can build on much of the prior experience gained with lower-level vehicle control algorithms and strategies (Browand, et al., 2004; Shladover, et al., 2011; and Lu and Shladover, 2011).

A closer analogy to the current work comes from the PATH CACC research for passenger cars, which included explicit consideration of managing the transitions associated with cut-in and cut-out maneuvers by unequipped vehicles (Milanés and Shladover, 2015). However, these studies only considered *ad hoc* coordination as the means to facilitate vehicle coupling. In the *ad hoc* coordination model employed by PATH, a vehicle operated in ACC mode until it was following another vehicle equipped with DSRC communication, at which point there was an automatic transition to CACC mode. The higher-level coordination strategies that could be used to find the other equipped vehicles and decide which position to take within the string of CACC vehicles were not considered in that prior research.

2.3.4 Energy ITS

The Japanese Energy ITS project began development for a demonstration of an automated four-truck platoon in 2008 (Tsugawa, Kato, and Aoki, 2011). In this project, both the steering and speed control on the trucks were fully automated, at least while following in the platoon. The lead truck could also operate using ACC speed control, automated steering, and limited automated obstacle avoidance capabilities (SAE Level 2), but manual control would still be required during platoon formation. The mid-term vision of the project (roughly the 2020 time frame) still required drivers to be present in each of the following trucks while operating in a mixed traffic environment, but the long-term vision (2030 and beyond) foresees operation in dedicated truck lanes where a driver would only be required in the lead truck.

Little detail was provided on the overall concept of how the platoon would form or exactly what the roles and responsibilities of the lead and following truck drivers would entail in the mid-term vision. However, based on the demonstration and testing scenarios, it was clear that platoons would form one truck at a time and provisions were made for trucks to join the platoon from the rear or into a middle position. One of the scenarios demonstrated did include the automatic detection of an obstacle in the roadway by the lead truck, followed by an automated lane change being performed by the platoon, and cut-ins by unequipped vehicles were also demonstrated.

Although the primary goal of Energy ITS was centered around demonstrating energy savings, the vehicle development aspects of the project touched on technical and design considerations during normal and sudden braking (Aoki, et al., 2012), and acceptable following distances (Hashimoto, et al., 2012) and driver interventions (Yamabe, et al., 2012) were also studied in the context of coordinated maneuvers such as braking. The following distance tests (Hashimoto, et al., 2012) were conducted using a passenger car, rather than a truck, following either a compact car or a minivan on a test track. With only 13 participants, the acceptable following time gaps at 52 mph (85 km/h) ranged from 0.3 to 0.8 s. Driver interventions during emergency braking were also studied in a driving simulator (Hashimoto, et al., 2012), and basically concluded that drivers were unable, in emergency braking scenarios (in excess of 0.6 g), to intervene and prevent a following truck from colliding with a lead truck when travelling at 50 mph (80 km/h) with a 0.45 s following time gap (10 m spacing).

2.3.5 SARTRE

The European Commission's SAfe Road Trains for the Environment (SARTRE) project (2009 to 2012) was led by Ricardo UK Ltd. and included the Volvo Car Corporation and Volvo Technology of Sweden (Chan, 2012). While most prior CACC and automated vehicle platooning projects focused on either passenger vehicles or heavy trucks, the SARTRE project explicitly set out to study platooning in a mixed setting to include both heavy and light vehicles.

SARTRE was based on the premise that the lead vehicle in the platoon would be a heavy vehicle, either a truck or bus, and driven by a professional driver trained to serve as a platoon leader (Bergenhem, Haung, Benmimoun, and Robinson, 2010, and Robinson, Chan, and Coelingh, 2010). The following vehicles in the platoon would then be fully automated. Although the following vehicle drivers were free to disengage from the driving task, they were required to remain available in case the platoon was required to dissolve due to unforeseen circumstances. The platoon leader was tasked with the additional responsibilities for platoon safety because the platoon leader was basically monitoring the forward roadway conditions, traffic conditions, and vehicle status and steering for the following vehicles. While platoons could contain a mix of heavy and light vehicles, for safety reasons, heavy vehicles would always occupy positions in the front of the platoon, and light vehicles would always occupy positions in the rear of the platoon.

The SARTRE use cases provided the first detailed analysis of platoon operational requirements (Robinson, Chan, and Coelingh, 2010) and human-machine interface requirements (Larburu, Sanchez, and Rodriguez, 2010), as well as a discussion on how local coordination could be used to match potential platoon followers with qualified platoon leaders through a third-party service. In creating use cases for forming or dissolving a platoon, it was thought to be necessary from a practical operation standpoint to allow join maneuvers into any position within the platoon, including front, middle, or rear, and split maneuvers from any given position. In the SARTRE concept, qualified platoon leaders would signal their intent to lead a platoon, while equipped followers searched for a leader. The follower would then request to join the platoon, and the platoon leader could then accept or reject their request. Once the request to join was accepted, the DVI would instruct the follower on how to join the platoon.

The initial inter-vehicle spacing requirements were determined using a driving simulator study that put the range of minimum comfortable following distance at 16.5 to 18 m when travelling between 50 and 75 mph (80 and 120 km/h), equating to a following time gap ranging from 0.5 to 0.8 s, and unsafe following distances at 7 m, equating to about 0.2 s. For the energy savings, aerodynamic simulations examined inter-vehicle spacings between 3 and 15 m, and the optimal fuel saving occurred between 6 and 8 m of spacing, which was in the range of following distances considered unsafe by drivers in the simulator study. The energy savings testing on a high-speed test track was conducted using inter-vehicle spacings between 5 and 15 m, and while peak fuel savings for the trucks occurred in the 5-6 m range, an 8 m gap still resulted in fuel savings ranging from 7 to 15 percent, only a few percentage points less than the peak.

2.3.6 CACC Research in the Netherlands

There have been a number of research activities related to the development of CACC systems based in the Netherlands recently. During the Grand Cooperative Driving Challenge (GCDC) in

2011, multiple SAE Level 1 CACC implementations were built and tested as part of the event (van Nune, et al., 2012), which was organized by TNO and the High–Tech Automotive Systems program, with sponsorship from the local and regional governments near the competition site in Helmond. Nine teams comprised of 11 universities and partners participated in the competition. Each team built their own CACC vehicle, and the entries included both cars and trucks, each with their own speed control system. Contestants were judged not only on how well their own vehicle performed, but on how well their vehicle cooperated with the rest of the vehicles in the platoon through V2V communication.

Other work conducted at Technical University (TU) of Eindhoven with SAE Level 1 CACC research vehicles developed by TNO examined the potential effectiveness of a pairwise CACC controller (Ploeg, 2014). The pairwise CACC controller only considers information broadcast by the immediately preceding vehicle, in contract to the truck platooning and CACC controllers developed in the previously discussed projects which depend on the information of the lead vehicle in the platoon or string being broadcast to all of the following vehicle.

Finally, TNO also published a whitepaper describing the business cases for automated truck platooning covering SAE Levels 2 through 5 (Janssen, Zwijnenberg, Blankers, and de Kruijff, 2015). The report described CACC as one of the enabling technologies in the roadmap to truck platooning that is currently under development by truck manufacturers in Europe. The vision laid out in the whitepaper suggests that two-truck platoons (SAE Level 2 or 3) could be operating at following time gaps as low as 0.3 seconds by 2020. The operating concept was limited to two trucks based on concerns over mixing longer platoons with general traffic, and equipped trucks would find each other based on either scheduled coordination (global coordination) or on-the-fly coordination (local coordination) through a third-party service.

2.4 Literature Gap Analysis

The prior literature on CACC and truck platooning has only discussed the operating concepts of these types of systems in the broadest of strokes and generally at the strategic level, rather than the operational level. As an example, while the literature discusses three general concepts which could be employed to facilitate string formation, *ad hoc*, local, and global coordination, very little has been done to define how string formation would work from the driver's point of view under any of these strategies. Sections 3-6 of this report examine how string formation, CACC cruising, string departure, and fault conditions might work from the operational point of view of the driver. If multiple operational alternatives exist, then the pros and cons of each alternative are discussed with consideration given to the potential implications each alternative might have on system safety, maneuver complexity, institutional and legal issues, sensor requirements, and DSRC message content.

3 CACC STRING FORMATION

3.1 CACC Equipped Truck Location and Coordination

3.1.1 Overview of Ad Hoc, Local, and Global Coordination Clustering Strategies

As described in Section 2 of this report, three vehicle clustering strategies were identified in the literature (Shladover, Nowakowski, Lu, and Ferlis, 2015): *ad hoc*, local, and global coordination. Most of the research involving light vehicle CACC has relied on an assumption of *ad hoc* coordination. With *ad hoc* coordination, the CACC system would function in an ACC mode most of the time, and the system would only switch to CACC mode when following a similarly equipped vehicle with which coupling was allowed. In this scenario, vehicles couple in whatever random sequence they happen to be traveling, and the probability of following another suitably equipped vehicle is directly related to the market penetration of equipped vehicles. Thus, at low market penetrations of DSRC and CACC, the probability of finding a suitably equipped truck to follow will be very low. Once the DSRC market penetration starts to increase, the probability of a CACC equipped vehicle finding a DSRC equipped vehicle to follow will increase, but the CACC strings will probably be *de facto* limited to two trucks until the market penetration of CACC also increases.

At low market penetrations, the second strategy, local coordination, could be employed to help cluster equipped vehicles and form longer CACC strings. In the local coordination scenario, CACC equipped trucks that are already on the freeway could communicate their locations and actively facilitate string formation. The local coordination approach has been discussed in the SARTRE project (Robinson, Chan, and Coelingh, 2010; Jootel, 2012; Larburu, Sanchez, and Rodriguez, 2010; Chan, 2012; and Brännström, 2013) and in the precursor work to the COMPANION project lead by Scania (Liang, Mårtensson, and Johansson, 2013). Local coordination could use the vehicle's DSRC radio for short range communication for vehicles within the 300 m broadcast range or cellular communication utilizing a back office service that would match nearby CACC equipped vehicles outside the range of DSRC communication alone. The local coordination service would then instruct one or more vehicles to speed up or slow down in order to facilitate CACC string formation. This strategy could also allow some flexibility in sequencing the vehicles by vehicle performance characteristics or driver preferences.

The third vehicle clustering strategy, global coordination, involves advance planning, starting from each vehicle's origin, to coordinate vehicles traveling from similar origins to similar destinations before the vehicles even enter the highway. Global coordination might adjust the vehicle's departure time, route, and/or travel speed, starting from surface streets, to maximize the amount of travel time that they can utilize the CACC system. The precursor work to the current COMPANION project led by Scania discussed the potential benefits of using global coordination (Larson, Krammer, Liang, and Johansson, 2013, and Larson, Liang, and Johansson, 2014). However, the implementation of this concept poses significant logistical challenges given the uncertainties in surface street traffic conditions and signal timing. Successfully timing the arrival of two or more vehicles at a particular highway entrance may be nearly impossible, and it certainly requires more extensive long-range communication and back-office coordination functionality that would not be needed in the *ad hoc* or local coordination cases.

3.1.2 Clustering Strategy Implications and Discussion

The selected CACC truck clustering strategy has broad reaching implications into DVI design, safety, and institutional and legal responsibilities. In terms of the DVI design, the *ad hoc* coordination scenario is simplest. With *ad hoc* coordination, the DVI only needs to show whether the preceding vehicle is equipped and what following time gap settings are available or currently engaged. Once local or global coordination is introduced, the CACC system must also provide an interface capable of allowing drivers to locate, select, and maneuver into a position where their CACC can couple with other equipped vehicles. Confirmation that the lead truck driver is willing to lead the CACC string may also be necessary, especially if the CACC system is going to instruct the lead truck to slow in order to allow other trucks to catch up.

The clustering strategy also has indirect implications on safety and efficiency since *ad hoc* coordination removes the ability to intentionally sequence the vehicles by engine performance, weight and braking performance, aerodynamics, or driver preference. However, if this information is communicated when using *ad hoc* coordination, the system can still employ strategies such as increasing the minimum allowable following time gap or decreasing the overall string performance to maintain safety at the expense of increased fuel consumption.

When considering the implications of the clustering strategy on legal responsibilities, the primary question is whether the driver of the lead vehicle in a CACC string has any additional duties or responsibilities above and beyond those present when driving solo. If CACC coupling is achieved through *ad hoc* coordination alone, then the lead driver may not even know that he is leading a string of followers. However, when using the more active local or global coordination methods, all drivers will be made aware of the formation of a string. If actively forming a CACC string does instill some additional legal burden on the lead truck driver, then the CACC DVI in the lead truck will need to notify the lead driver when new following vehicles wish to join the string and confirm the lead driver's willingness to accept each new CACC follower.

The SARTRE project report on policy issues (Dávila, 2013) discussed the responsibilities of the lead truck driver, but there are significant differences between the SARTRE automation concept and the current truck CACC concept. In the SARTRE concept, the lead driver was essentially monitoring the road and actively controlling the steering and speed for all of the following vehicles, whose drivers were then free to disengage from the driving task. Thus, the lead vehicle driver clearly accepted additional responsibilities for leading the platoon and monitoring the status of the following vehicles. During platoon formation, the lead driver needed to actively confirm a willingness to lead the platoon and actively confirm the joining of each new vehicle to the platoon using the DVI. The less ambitious CACC modes of operation planned for the current project should make it possible to simplify this situation.

In the current CACC concept, all drivers are still responsible for steering their vehicle and maintaining continuous visual monitoring of the road and traffic conditions, but the following drivers' fields of vision and ability to monitor the roadway for hazards will be impaired by the lead trucks. An argument could be made that the lead truck drivers will need to be more vigilant in monitoring traffic conditions, and they will need to anticipate and react to potential problems sooner to avoid potentially getting into hard braking situations. The lead truck driver may also need to avoid certain maneuvers, such as a quick lane change when approaching slowed or stopped traffic, as this would lead to a situation in which the following truck driver is likely to be surprised and unable to react in time. So, similar to the analysis in SARTRE, the lead driver in a CACC string is taking on some additional responsibility, which may eventually be found to have liability or insurance implications in the event of a crash as discussed in the SARTRE report on policy issues (Dávila, 2013).

Additionally, both the local and global coordination strategies could potentially utilize third-party brokers or services to facilitate locating nearby equipped trucks at very low market penetrations of DSRC and CACC technology. Since the DSRC communication range is only about 300 m, the third-party service would need to integrate cellular or other longer range communication with a back office database tracking the locations of equipped trucks that are looking for an opportunity to form a CACC string. While the SARTRE project did look at some of the issues related to the commercial viability of third-party services to help coordinate platoon formation (Brännström, 2013), little has been discussed regarding the potential responsibilities or liability exposure of these services. For example, what obligation does the third-party service have in verifying that all of the trucks using the service are well maintained, or what obligation does the third-party service have in verifying that the driver of the lead truck (or any of the following trucks) has not exceeded their hours of service? Even if a third-party service is not used, this type of potential liability exposure may dictate that ancillary information about vehicle maintenance or driver hours of service remaining be transmitted and considered during CACC string formation.

3.1.3 Project Recommendation

After considering the three CACC clustering strategy alternatives, the CACC system that will be designed and implemented in this project should support both *ad hoc* coupling and limited local coordination utilizing the DSRC communications. Longer-range coordination, beyond 300 m, will be unnecessary in this project because the on-the-road testing will only involve scenarios in which the equipped trucks will be within line of sight of each other, and researchers will be present in the vehicles to assist in communication and coordination. However, the driving simulator experiment may consider local coordination scenarios in which the communication would clearly exceed the 300 m range that would be offered by DSRC communications.

A production system may require DVI functionality to select between ACC and CACC modes of operation, since there may be times when the drivers wish to use the ACC rather than forming a CACC string with other equipped trucks. However for this project, the CACC clustering coordination part of the system will, at minimum, need to be capable of the following three functions:

1. After the driver activates the CACC system, the system will need to automatically locate each nearby CACC equipped truck (or string) based on their DSRC broadcasts of their location and heading information.

2. The DVI will then display a list or graphical representation of the nearby CACC equipped trucks (or strings) for the driver to select a truck with which to couple. In the longer term, but not necessarily for the system being designed and implemented in this project, the DVI may need to display and/or filter on parameters such as the desired string speed, truck performance characteristics (weight, braking performance, and engine power), and driver preferences for string position (leader or follower), so these parameters need to be considered for inclusion within a string coordination message set.

3. Once a target truck (or string) has been selected, the CACC system in each truck will need to instruct the drivers on how to proceed, directing one or more trucks (and/or drivers) to slow down, speed up, or change lanes via the DVI that needs to be designed to be clear and easily understood.

3.2 CACC String Formation

3.2.1 Lead Truck Assignment Alternatives

CACC string formation occurs when two or more single trucks wishing to couple have been located, and no local CACC string exists. The primary issue during this initial CACC string formation maneuver is selecting which truck will be the leader and which trucks will be the followers. Three alternatives were considered for deciding which truck becomes the lead truck:

1. The lead truck assignment could simply be determined according to the initial location. Whichever truck happens to be in front or furthest ahead along the roadway defaults to the lead truck.

2. The lead truck assignment and subsequent truck ordering could be determined based on the truck attributes of engine performance, weight and braking performance, or aerodynamics. When it comes to stopping the CACC string, placing the trucks with the worst braking performance up front will increase safety, but in terms of overall efficiency, it may make sense to place the most aerodynamic vehicle in front. An argument can also be made to order the trucks from lowest to highest engine power to total mass ratio (including tractor, trailer, and load), so that the lead trucks can't pull away from the following trucks when accelerating or on hilly terrain.

3. The lead truck could be assigned according to preset driver or fleet operator preferences. In the truck CACC concept, the following trucks will experience the most fuel efficiency gains, but the lead truck will likely be compensated with payments from the following trucks. Still, some drivers may prefer the lead truck position to a following truck position, and the CACC system may need to take those preferences into account when forming the CACC string.

3.2.2 Project Recommendation

After considering the three alternatives for lead truck assignment, the second option can be disregarded for this project. Since all three trucks used in this project will be identical, with similar performance characteristics, the CACC system that will be designed and implemented in this project will not need to consider differences in truck performance. However, the project will desire some intentional ordering of the vehicles during the on-the-road testing since the testing protocol involves allowing naïve truck drivers to experience each of the following positions in the CACC string. This requirement could be accomplished using either the first or third alternative, and the system design should incorporate both options.

First, the lead vehicle assignment (and potentially the vehicle ordering) should be configurable for each truck as a driver preference, but since each truck would be configured independently, the possibility of conflicting preferences would exist, such as when all of the trucks are configured to request the leader assignment. Thus, as a backup, leader assignment and vehicle order should also take into account each vehicle's starting location so that lining up the vehicles in the correct order prior to engaging the CACC system will result in the desired string order, regardless of the driver preferences. This string formation strategy would require including both vehicle location and driver preference for leader or follower position in the desired communication message set.

3.3 CACC String Join Maneuver

3.3.1 Local Coordination Maneuver Alternatives

The first phase of the CACC string join maneuver involves local coordination between the existing string and the joining truck. There are several key system design issues associated with the local coordination phase of the join maneuver. Once a potential coupling is proposed through local coordination, the truck drivers wishing to couple must be instructed on how to find each other in traffic since they could be up to several miles apart and in different lanes. In the precursor work to the COMPANION project (Liang, Mårtensson, and Johansson, 2013), the simulations conducted on the potential benefits of local coordination assumed that the following truck would always be given instructions to speed up to catch up with the lead truck. However, this design is predicated on the assumption that the upstream truck (or string) is travelling below the speed limit; otherwise, the downstream truck (or string) would need to violate the speed limit to catch up to the upstream trucks. At least in the U.S., it's more likely that any trucks on the highway will already be traveling at the speed limit or at their top speed, and for local coordination to work, the message sent to the upstream truck (or string) will need instruct those drivers to slow down to allow the downstream trucks to catch up. Having the upstream truck (or string) slow down may also be more fuel efficient than instructing other vehicles to speed up, but there will also be a cost in terms of travel time for the trucks being instructed to slow down.

Second, when giving a truck (or string) instructions on how to couple, the instructions could be presented to the driver on the DVI, relying on the driver to adjust the vehicle speed. Alternatively, if the C/ACC systems are engaged on any or all of the trucks, the set speeds could be automatically adjusted for each of the trucks. If the drivers of the upstream trucks must be relied upon to slow down in order to facilitate coupling, then the system must have the ability to detect if those drivers are not complying and abort the coupling process. However, the maneuver may not be able to totally rely on the C/ACC system being active throughout the join maneuver. The drivers may need to periodically disengage the system during the join maneuver in order to make lane changes or otherwise maneuver into position.

3.3.2 Join Maneuver String Position Alternatives

In the second phase of the CACC string join maneuver, the joining truck is added to the existing string and takes a position within the string. The system could potentially allow new trucks to join from the rear, from the front, or into the middle of the string. Allowing new trucks to join in any position would allow the trucks within the CACC string to be ordered by weight and braking performance, engine performance, aerodynamics, driver preference, or even destination, but there are also technical, practical, and potentially efficiency implications associated with each option.

From a technical standpoint, new trucks can join an existing CACC string most easily from the rear, becoming the new trailing truck. In this scenario, the operation of the existing string is minimally impacted, and the driver of the joining truck simply needs to change into the correct lane behind the existing string, after which the CACC system can automatically couple and close the gap. However, from a practical application standpoint, joining an existing CACC string may be difficult in dense traffic if there are other vehicles closely following the existing string. The truck driver wishing to join may not be able to get into position easily or quickly.

Joining a new truck to the front of an existing CACC string, so the new truck becomes the new leader, could allow a driver with a preference to be the leader to join an existing string where the other drivers prefer to be followers. In dense traffic, it could also be practical since the current leader of the CACC string can always slow down to open up a gap for the joining truck, if the joining truck needs to change lanes into the existing string's lane. However, joining to the front of a CACC string is more technically challenging than joining from the rear because a transition of the string leader role must occur. As shown in Figure 3.1, before the join maneuver, the following trucks incorporate the string leader's broadcast data into their own control algorithms. At some point during the join maneuver, there will need to be a transition when all of the following trucks stop listening to the former lead truck and start to listen to the new lead truck, as depicted in Figure 3.2.

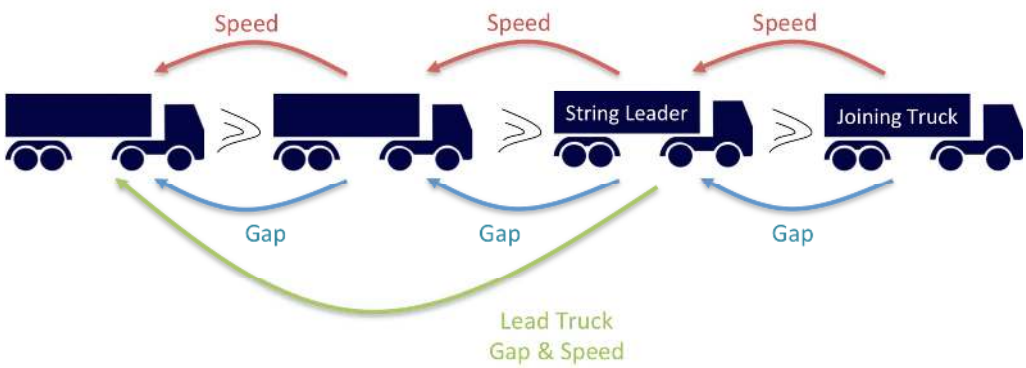

Figure 3.1. CACC Information Flow Pre-Join Maneuver.

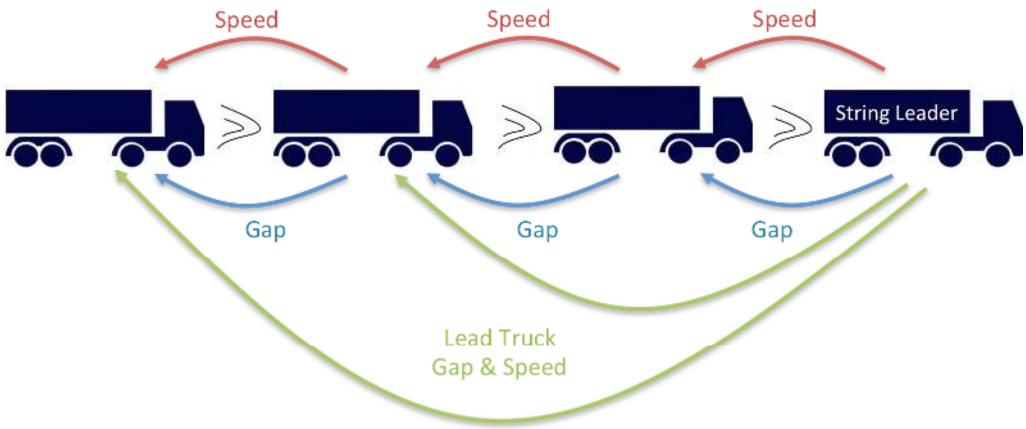

Figure 3.2. CACC Information Flow Post-Join Maneuver.

Finally, joining a new truck to the middle of an existing CACC string could allow the trucks to be more sensibly ordered in terms of performance characteristics or destination, and in traffic, it is also practical since the trucks in the CACC string can open up a gap for the joining truck to merge into the existing string's lane. However, this maneuver is technically challenging, requiring quite a bit of coordination among multiple trucks. The joining truck will need to consider the information provided by the future lead truck, the future preceding truck, the future following truck, and any preceding vehicles in the joining truck's current lane. The future following truck needs to consider the information provided from the lead truck, the immediately preceding truck, and the joining truck. The worst situation that could arise happens when the joining truck starts to change lanes, and any of the preceding vehicles, either those in the string or those in the joining truck's lane, need to decelerate. Furthermore, most of the information needed during this maneuver will likely need to rely on DSRC communications alone because the targets that must be tracked are distributed across two lanes and may not be within the field of view of a particular truck's radars or lidars.

As a final consideration in this scenario, lane changes in the CACC concept are performed manually by the driver, and drivers may not be comfortable with performing a lane change into a tight gap or even performing it while under automated CACC speed control. The extra gap that must be opened to allow a manual lane change into the middle of a CACC string and the subsequent gap closing maneuver will also have fuel efficiency implications for all of the trucks in the CACC string behind the position of the newly joined truck.

3.3.3 Join Maneuver Gap Setting Transition

As the joining truck moves into position within the string, the C/ACC system will transition from ACC, with longer gap settings, to CACC, with shorter gap settings. There are several ways to handle this transition. First, the ACC and CACC systems could remember the last used gap setting independently, and a transition between modes will always revert to the last used setting. This strategy may work well when a truck only has a single driver, rather than being shared across drivers. Second, the system could always revert to a particular gap setting when transitioning between modes, and then rely on the driver to select the desired gap. For example, when transitioning from ACC to CACC, the system may always default to the longest CACC gap setting because it would provide the least aggressive change, and similarly, when transitioning from CACC to ACC, the system may always default to the shortest ACC gap setting. Finally, the system could maintain the current relative gap setting across the transition. Thus, if the middle gap setting in ACC was selected, the system would automatically transition to the middle CACC gap setting. For this project, the last option will be implemented based on technical feasibility. Since the trucks used in this project already utilize a factory ACC DVI that cannot be easily modified, the relative gap setting transition strategy will ensure that the original ACC DVI does not display incorrect or conflicting information when in CACC mode.

3.3.4 Project Recommendations

The CACC string join maneuver can be considered as having two phases. In the first phase, the existing string and the joining truck must locate each other on the highway and coordinate speeds. While the existing literature has assumed that the joining truck will speed up to catch up to the existing string, it is more likely, at least in the U.S., that the upstream trucks will need to slow down to allow the downstream trucks to catch up, otherwise, the downstream trucks may never be able to catch up, at least without violating the speed limit. During this phase, the truck (or string) coordination target speeds could be displayed to the driver, or the target speeds could be automatically provided to the CACC system as the set speed. The CACC system design and implementation in this project should include both options, displaying the target coordination speed to the driver and automatically using that speed for the CACC set speed, because the CACC system may need to be disengaged by the driver during the coordination phase of the join maneuver. For example, the driver may need to disengage the speed control when making a lane change, but then wish to resume the speed control after completing the maneuver.

In the second phase of the CACC string join maneuver, the driver must merge into the destination position. Although there may be advantages to allowing a new truck to join into any position within the existing string, for this project, the CACC system design and implementation will only consider the least technically challenging case, in which new trucks join the string from the rear. However, the driving simulator study may also consider the alternate join maneuver scenarios, particularly the scenario when the joining truck merges into the middle of the CACC string.

3.4 CACC String Formation and Join Maneuver Summary Narrative

From the driver and system perspective, one or more truck drivers will activate the C/ACC system, set their desired speed and ACC gap setting. Drivers may also pre-set a preference for leader or follower to be used when forming a new string. Once the C/ACC system is active in ACC mode, the CACC local coordination feature will search for additional trucks (or existing strings) within communication range with which to couple. During the local coordination search mode, the C/ACC systems will exchange any messages necessary to accomplish the following tasks:

- Verify CACC compatibility.
- Indicate each truck's location, speed, and string position.
- Indicate each truck driver's preference for leading or following.

- Verify that adding another vehicle to an existing string will not exceed the maximum string length.

The joining driver will then be displayed a list and possibly a simple graphical representation of trucks or existing strings with which coupling is possible. Once a joining truck driver selects a lead truck (or existing string) to couple with, the local coordination feature will confirm with the lead truck and instruct the lead truck (or string) to slow down, while instructing the joining truck (or string) to speed up. The lead driver of the string and the driver of the truck wishing to join the string will each be displayed a target speed and target lane in which to travel during the coordination. Additionally, the target speed during the coordination maneuver will automatically be set as the C/ACC set speed. In addition to the target coordination speed, the DVI will also need to display the relative location, lane, distance, and if necessary, an indication of when the joining truck driver should change lanes to get behind the lead truck (or string).

Once the joining truck is directly behind the lead truck (or existing string), the CACC system's vehicle following mode will engage automatically, and the lead truck's former set speed will be restored and relayed to all of the following trucks. Once in the string, the drivers will be able to select any of the available CACC following gaps.

For demonstration purposes, the CACC system should track the time and mileage spent travelling in the string for each truck as a representation of an electronic payment transfer system that could be implemented to compensate the lead truck driver, whose truck will not gain as much fuel efficiency benefits as the following trucks. As trucks leave the string, the lead truck should receive a message regarding how much time or distance the departing truck spent travelling in the string and how much it paid for that privilege.

4 CACC STEADY-STATE CRUISING

4.1 CACC Gap Settings Discussion

The purpose of forming a CACC string is to enable shorter following gaps, allowing for both increased fuel efficiency and increased lane capacity during steady-state cruising. Thus, most of the time spent driving in a CACC string will be spent in steady-state cruising, and the primary research concern in the steady-state cruising scenario is related to the driver acceptance of and performance with shorter following gaps. During steady-state cruising, driver performance will mostly consist of steering performance, since the driver is required to continue steering the vehicle even under CACC. Prior PATH research focused on passenger vehicle CACC showed that drivers were fairly comfortable at following time gaps down to 0.6 s, but such short following time gaps may be less acceptable for truck drivers given the obvious visual occlusion that will be present when following another truck so closely.

Defining the specific gap settings to be used in this project is unnecessary as part of this report. Later stages of this project will conduct two on-the-road CACC experiments, both primarily focused on steady-state cruising, and both experiments will require that the driver be able to adjust the following time gap setting. The first experiment will focus on human factors on-the-road testing, examining driver comfort levels at following time gaps down to 0.6 s as a function of string position, while the second experiment will focus on fuel efficiency testing, examining the fuel savings that can be achieved over a range of similar gap settings. Prior to the on-the-road testing, driver comfort levels and driver performance at the various following time gap settings will be tested in the driving simulator experiment, providing the project team with some initial data on whether the targeted 0.6 s following gap is within the potential range of driver acceptability. The range of following gap setting options for the on-the-road experiments can then be adjusted if necessary.

4.2 CACC DVI Design Discussion

There are two primary DVI concerns in the CACC constant cruising scenario. The first concern is simply providing the driver with enough situational awareness feedback to understand both the status of his vehicle and the status of the CACC string of vehicles. Maintaining situational awareness really becomes critical, not necessarily during cruising, but when cruising is interrupted by string join or split maneuvers, cut-ins, or system faults. In any one of these cases, the driver is most apt to notice the vehicle (or string) slowing down abruptly or the gap between vehicles being automatically adjusted without driver input, and the DVI needs to clearly convey why.

The second concern during constant cruising is the potential impact that reduced visibility might have on driver workload, vigilance, fatigue and lane keeping performance. Because the following truck drivers will have limited forward view at the short following time gaps enabled by the CACC, it is possible that the driver's steering workload will be increased, especially in curves, leading to more rapid fatigue and decreased vigilance over time. While a specific examination of driver workload, vigilance, and fatigue issues is not planned during the on-the-road testing in this project, the driving simulator experiment may evaluate whether the DVI could be used to provide preview to improve driver comfort and performance. Several ideas for providing the following truck drivers with preview have been discussed. One option would be to provide a video feed from the front truck in the string. The video feed would allow the following truck driver to see both the upcoming road geometry and traffic. Another option would be to provide a graphic display with map information that informs the driver about upcoming road geometry and curves. If feasible, the resulting DVI design will be incorporated into the trucks during the on-the-road experiment.

4.3 Cut-Ins By Unequipped Vehicles

Past PATH on-the-road experiments and testing have shown that cut-ins by unequipped vehicles are nearly unavoidable, even at following time gaps of 0.6 s. Typically, these cut-ins occurred near highway entrance and exit ramps by vehicles entering or exiting the highway. In this current project, cut-ins by unequipped vehicles will almost certainly disrupt CACC string cruising during the on-the-road testing, even in moderate traffic, so the CACC system must be designed to automatically detect and react to cut-ins.

During a cut-in, a forward sensor on the truck immediately behind the cut-in will detect the new target, recognize that it is an unequipped vehicle, and change its following strategy. The strategy that has been used in the past for cut-ins is to temporarily split the CACC string. The truck that is immediately behind the unequipped vehicle becomes the new string leader for all of the following trucks, while increasing its following time gap to a longer setting more appropriate for ACC following. While still in communication range of the now-split-off upstream string, the downstream string leader should still listen to the DSRC broadcasts of the upstream string, using the information provided to gain preview knowledge of any sudden speed changes, but the new string leader will primarily be following the unequipped cut-in vehicle in ACC mode.

How well the implemented CACC system can automatically handle the cut-in will depend on the field of view of the forward sensors on the trucks and the quality of the target tracking algorithm. A wider field of view will result in the detection of the cut-in vehicle sooner, resulting in a smoother transition to the longer gap settings, while a narrower field of view will result in later detections and more abrupt transitions. In either case, the driver will still be responsible for monitoring for cut-ins and disengaging the CACC system through manual braking should the system fail to respond appropriately. A wide-field-of-view short range laser scanner system will be considered as an additional sensor to provide early information about cut-ins.

A cut-in scenario will generally be followed by a cut-out scenario, since most drivers prefer not to drive between heavy trucks for an extended period of time. Once the unequipped vehicle changes lanes, merging out of the path of the CACC string, the CACC system could either automatically re-join the two CACC strings or keep the two strings separate. Since cut-ins will occur frequently in practice, having the system automatically re-join the strings would probably constitute the best design; however, situational bounds will be necessary. For example, a re-join would not make sense if the split-off string falls so far behind the original string that DSRC communication is lost or the distance between the two strings can't otherwise be easily or efficiently closed.

Additionally, for demonstration purposes, the tracking of CACC string follower time and miles accumulated for financial records should be suspended or redirected from any followers behind the cut-in vehicle to the new string leader as appropriate. Finally, the German KONVOI project showed that frequent cut-ins were such a large issue that it negated most of the expected gains in fuel efficiency that truck platooning offered. One research question that might be examined during the on-the-road testing in this project is whether there are more or less fuel-efficient control strategies for dealing with cut-ins, but even if multiple strategies cannot be tested, the on-the-road testing should carefully measure the impacts of a cut-in on fuel consumption.

4.4 CACC Cruising Summary Narrative

Steady-state cruising is what truck drivers will be doing most of the time while the CACC system is engaged. Once a string is formed, the drivers will still be tasked with actively steering their vehicles and monitoring vehicle status and traffic conditions, but steady-state cruising should only be interrupted when trucks join into or split from the string or when an unequipped vehicle cuts in between the following trucks in the string. Because cut-ins in on-the-road testing will be unavoidable, the CACC system needs to be designed to automatically handle a cut-in by splitting the string and commanding the new lead truck, directly behind the cut-in, to fall back to a longer ACC gap setting and following strategy. Once the unequipped vehicle departs the lane, the CACC system can automatically re-join the two split strings and close the gap. The driver will still be responsible for monitoring for potential cut-ins and disengaging the CACC system through manual braking should the system fail to respond appropriately.

5 CACC STRING SPLIT MANEUVER

5.1 Lead Truck Departs

When approaching a highway exit, one or more of the trucks in the CACC string may wish to depart the string. The complexity of the string split maneuver depends on which truck driver wishes to exit the string. If the lead truck driver in the string wishes to depart, one option is that the driver of the lead truck simply needs to change lanes into an open space in the adjacent lane. Once the forward sensors in the second truck in the CACC string lose sight of the lead truck, the CACC system will automatically split the string, and the second truck will become the new lead truck for the remaining trucks in the string. The CACC system in the second truck would also switch from a CACC following strategy, in which shorter gap settings would be available, to an ACC following strategy, in which only longer following gap settings would be available. The gap selection and transition strategies when going from ACC to CACC or vice versa were previously discussed in Section 3.3.3, and for this project, the relative setting will remain the same. Thus, if the CACC was set to the shortest gap setting, the system would retain transition to the shortest setting for ACC.

In the scenario described above, it is also possible that the lead truck driver may need to temporarily disengage the C/ACC system and manually adjust the truck's speed before making the lane change. This variation should have little impact on the maneuver because the lead truck can always operate either in C/ACC mode or while being manually driven. The lead truck will continue to lead the CACC string until the lane change is complete, and the following trucks would simply continue operating normally until the second truck is designated as the new lead truck for the string. Once the second truck is designated as the new lead truck, its C/ACC system will revert to an ACC following gap, and the set speed on that truck will dictate the maximum speed of the string.

Once the original lead truck leaves the CACC string, the CACC systems in the following trucks will stop tracking time or miles accumulated behind the former lead truck, and start tracking time or miles accumulated under the new lead truck. In a production system, these systems would also finalize any payments from the followers to the former lead truck. The driver of the new lead truck, formerly the second truck in the string, will then be notified that he is now receiving payments from the remaining followers.

5.2 Middle Truck Departs

When one of the middle truck drivers in the CACC string wishes to depart, the maneuver will affect all of the following trucks. If possible, the driver may simply perform a lane change with the CACC system still active, but it is at least as likely that the driver will want to return to manual speed control and slow down while timing the lane change with an appropriate gap in the adjacent lane's traffic. If the driver is able to perform the lane change without deactivating the CACC system, then the CACC string will be least impacted. Once the departing truck exits the lane it will stop tracking time or miles spent following the string leader and will finalize any payments to the leader, and the following trucks will simply close the gap left by the departing truck.

However, in the case when a middle truck driver needs to take over manual speed control before changing lanes, then the original CACC string will split into two strings as soon as the departing truck driver disengages the CACC system by braking or otherwise deactivating the system. The departing truck will then become the new lead truck for the second CACC string until the departing truck changes lanes. When the string splits, the CACC systems in the departing truck and all of the following trucks will temporarily pause the tracking of time and miles spent following the original CACC string leader until the departing truck completes its lane change. The following trucks will then need to rejoin the former string and resume tracking time or mileage to be credited towards the string's original leader (unless they have fallen so far behind the string leader that this is not practicable).

What happens next for the departing truck depends on a number of factors. If the departing truck disengaged the C/ACC prior to performing the lane change, then the truck will simply remain under manual control until the C/ACC system is reengaged. Once the C/ACC system is reengaged or if the truck changed lanes with the system still engaged, then the system behavior will depend on what is encountered ahead of the truck in the new lane. If nothing is in sensor range, then the system will default to ACC speed regulator mode, accelerating to the maximum speed that was previously set by the driver. If an unequipped vehicle is in sensor range, then that vehicle becomes the new target for ACC following at the longer ACC gap setting that was previously set by the driver. Finally, if another CACC equipped vehicle is in sensor range, then that vehicle becomes a candidate leader for joining or forming a new CACC string.

5.3 Trailing Truck Departs

When the last truck in the CACC string wishes to depart, the maneuver will have no effect on the other trucks in the string. The driver of the last truck may simply brake or perform a lane change to an adjacent lane. If the driver brakes, the CACC system will be deactivated and the truck speed will be under manual control. Alternatively, if the driver performs a lane change with the CACC system active, the system will switch to ACC mode as soon as the truck changes lanes and the forward target is lost.

Similarly to the departure of a middle truck, what happens next depends on whether the C/ACC system was disengaged and what is in front of the departing truck in its new lane. If the C/ACC system was disengaged, then the truck simply remains under manual control. If the C/ACC system remains engaged and nothing is in sensor range, then the system will default to ACC speed regulator mode, accelerating to the maximum speed that was previously set by the driver. If an unequipped vehicle is in sensor range, then that vehicle becomes the new target for ACC following at the longer ACC gap setting that was previously set by the driver. Finally, if another CACC equipped vehicle is in sensor range, then that vehicle becomes a candidate leader for joining or forming a new CACC string.

5.4 Driver Notification of Intention to Depart

One major CACC system design question related to the string split maneuver is whether the departing driver needs to formally indicate their intention to depart the string, either through turn signal activation or some other button press on a secondary display. If the departing truck is the lead truck or one of the middle trucks, then signaling an intention to depart the string may be beneficial in priming the CACC system for the maneuver and triggering a pause in the tracking of payments to be transferred between drivers.

More importantly, signaling intent to leave allows advance notification of the maneuver to be sent to the drivers of the following trucks. Although all CACC truck drivers will still be responsible for actively steering their trucks, monitoring their truck's status, and monitoring traffic conditions while cruising in a CACC string, drivers may benefit from advance warning of a change in the string status, especially if it is the lead truck that is departing and the second truck in the string will soon need to take over as the lead truck. If the departing truck is one of the middle trucks in the string, then the advance notification may be less important, but still cues the following drivers as to why the string may be slowing down or speeding up. Finally, if the departing truck is the last truck in the string, then there is no advantage in the driver signaling an intention to depart the string because a departure of the trailing truck will have no impact on the remaining trucks in the string.

The requirement for notification of intent to depart the string, specifically for the lead truck driver, should be predicated on whether the lead truck driver bears any additional or heightened responsibilities as the leader of a CACC string because only the driver of the lead truck will have an unobstructed view of the roadway and traffic conditions ahead. As an example, if the lead truck driver decides to change lanes to pass a slower moving vehicle, does the lead driver need to inform the rest of the string to do the same, or does the string simply split apart and manually rejoin after each truck has passed the slower moving vehicle? Even with moderate traffic density, the latter option may be the only option given the space requirements necessary for even a three-truck string to change lanes. Similarly, if there is an obstacle in the road in the travel lane, should the lead truck driver be obligated to decelerate the string or issue an alert to the following drivers, rather than simply changing lanes at speed, a maneuver that is likely to reveal the object in the roadway to the second truck driver with little or no time to react?

For this project, intent to depart the string may be tied to turn signal usage or a separate button on the DVI, but in both this project and in a practical deployment scenario, the CACC system cannot rely on a driver always signaling his intent to leave the CACC string. Since CACC drivers always remain in control of steering the vehicle, a driver could always impulsively decide to merge out of the string without first signaling intent, and the system would need to detect the event and inform any affected following drivers as soon as possible.

5.5 Automatically Joining Previous or New Strings

Another CACC system design question is related to how the systems in the following trucks react after a string has been split and the departing truck has left the lane, particularly when the departing truck is a middle truck and the driver disengaged the CACC system in order to change lanes. When this happens, the trucks that were following the now-departed truck could continue in their newly formed string, or they could automatically rejoin the original string. As long as other vehicles have not cut into the lane in front of the departing truck and the distance to close is reasonable, then it makes the most sense for those trucks to remember that they were once part of the original string and automatically rejoin that string. From the perspective of the drivers of the following trucks, they had already agreed to be part of the string, and the departure of a preceding truck should have little effect on their desire to continue in the string.

The same question arises for the departing truck, if the departing truck changes lanes with the CACC system active and there is another equipped truck (or string) within sensor range in the new lane. In this case, there are two potential options for the behavior of the CACC system. First, the CACC system could use *ad hoc* coordination to automatically couple with the truck or string in the new lane, or the CACC system could revert to ACC mode until the driver requests or confirms that he wishes to initiate a join maneuver. To what extent driver confirmation should be required in this scenario may depend on the financial implications of joining the new string. If there were no financial implications associated with joining a CACC string, then automatic ad hoc coupling would make the most sense. However, assuming that there are financial implications to forming a CACC string, then the situation becomes more complex. Once the departing truck leaves its former string, the system will stop tracking time or miles spent following the leader of that string, and the system will finalize payments to the former lead truck. Assuming that there are financial implications of joining the CACC string in the new lane, then the driver may or may not wish to initiate a join maneuver depending on the driver's goals in leaving the original string. As an example, the driver may not wish to join another CACC string because he is in the process of making several lane changes in order to reach an exit.

For the experimental implementation in this project, the CACC systems on the trucks will be able to automatically couple using ad- hoc coordination (in addition to using local coordination when the trucks wishing to couple are not directly behind each other). The CACC system will always couple with equipped preceding trucks and simply track how much time is spent following any string leader, since the primary focus of this project is not on the business transaction system.

5.6 CACC String Split Maneuver Narrative

Any trucks in the CACC string may depart the string at any time, and the effect that the departure will have on the string will depend on which truck is exiting the string. In an ideal departure, the driver of the departing truck will signal their intent to exit the string by activating the turn signal or otherwise indicating so using the DVI. If a driver signals their intent to depart, then any following drivers in the string will be notified of the maneuver through their DVI. In the least disruptive case, the departing truck simply changes lanes, and the following trucks close the gap. However, in some case, the departing truck may need to revert to manual speed control before changing lanes. In the case when the departing truck is a middle truck in the CACC string, the string will need to be temporarily split into two strings, with the departing truck leading the second CACC string under manual control until it fully departs the lane. Once the departing truck changes lanes, the trucks that were following it will rejoin the original CACC string and close the gap left by the departing truck.

6 FAULTS, ERRORS, AND ABNORMAL OPERATING CONDITIONS

6.1 CACC System Disengagement and Kill Switch

6.1.1 Overview

There should be multiple means to disengage the CACC system's active control of the vehicle speed including activating the brake, pressing the C/ACC cancel switch, pressing the C/ACC power switch, or pressing the emergency kill switch (only to be installed for research testing). In each of these cases, the CACC system should stop actively controlling the vehicle speed, returning speed control to the driver. However, ideally, the DSRC system on the truck should continue to broadcast the truck's basic safety message (BSM) and any additional CACC-specific messages defined within this project in case the truck is part of a CACC string, but the DSRC system should be prevented from broadcasting false information in the event that the emergency kill switch is activated.

6.1.2 Brake Activation and C/ACC Cancel Switch

The primary means to disengage the C/ACC system is for the driver to depress the brake pedal or to press the C/ACC system cancel button. Either of these actions should stop the system from actively controlling the vehicle speed, but should leave the C/ACC system powered on such that all settings (desired set speed and following gap) are retained the next time that the system is engaged with the C/ACC system resume button. The effect of a C/ACC system disengagement on the rest of the CACC string depends on the position of the truck that is disengaging the system.

If the driver of the lead truck in a CACC string disengages the C/ACC system, then there should be no impact on the rest of the string. The driver of the lead truck is always free to use the C/ACC system (defaulting to ACC gap settings) or to drive completely manually. The following trucks should seamlessly follow the lead truck, even as it switches between manual and C/ACC speed control. If the driver of any other truck in the CACC string disengages the CACC system, then that truck will essentially split off from the CACC string, and any trucks behind it will be affected. The split off truck will become the new lead truck, driven manually, for any followers.

6.1.3 C/ACC Off Switch

A second means to disengage the CACC system is for the driver to turn off power to the C/ACC system using the C/ACC On/Off button. Typically, powering off the C/ACC system would erase the current settings (set speed and gap preference), and turn off the C/ACC driver display elements. However, even with the C/ACC system off, the truck should still be able to serve as a CACC string leader, and the supplementary driver display, used for finding other equipped vehicles, showing the status of followers, and tracking payment transactions between trucks, would need to remain active.

6.1.4 *Kill Switch*

A third and final means to disengage the CACC system is for the driver to press an emergency kill switch, and typically, this means of disengaging the CACC system would only be applicable during research and development. Ideally, the kill switch would only be used if the brake, cancel, or C/ACC off switch was ineffective at disengaging the automated control. The kill switch would then provide the last line of defense in physically interrupting the CACC system's output commands to the vehicle, returning full control to the driver.

However, the design of how the kill switch interacts with the CACC control system must also take into consideration what happens to any DSRC broadcasts by the vehicle. Once the kill switch has been activated, the system must be designed to ensure that either the information being broadcast actually represents the current state of the vehicle or that the other vehicles listening to the broadcast are made aware that the kill switch has been activated. As an example, in a scenario when the kill switch was activated because the CACC controller would not disengage, then any information provided by the CACC controller to the DSRC radio would be suspect and may not represent the current state of the system. Although this has been flagged as a potential issue here, specific recommendations will depend on the system design and how information to be broadcast over the DSRC is gathered, filtered, and flowing between the various processors and components in the system.

6.2 Accelerator Pedal Override

All ACC systems allow the driver to temporarily override the system's speed and gap control, without disengaging the system, simply by engaging the accelerator pedal. In passenger vehicles, this override method is particularly useful in adjusting the vehicle's speed prior to and during a lane change, but with ACC the time gaps being maintained by the system are significantly longer than the time gaps that will be maintained in CACC. Multiple strategies could be considered for the accelerator pedal override.

First, the CACC system could function exactly how current ACC systems function, allowing the driver to override the vehicle's speed and following gap with the accelerator pedal. Since the driver is the one overriding the system, then the driver is assuming responsibility for the chosen maneuver and following gap. This strategy could be combined with feedback or a forward collision warning given to the driver. As an example of feedback, Nissan equips some vehicles with a Distance Control Assist system. With this system, when the driver begins following a lead vehicle too closely, counter pressure is applied to the accelerator pedal to prompt the driver to release. Similarly, an audible Forward Collision Warning (FCW) system could be enabled when the driver is using the accelerator pedal to override the CACC system. (Typically the FCW system would need to be disabled or at least adjusted to be less sensitive when following at the shortest CACC gap settings to avoid frequent false alarms.)

A second and alternative strategy is that the CACC system may set a minimum following gap, beyond which the accelerator pedal override is disabled. For example, if the shortest available CACC gap setting is 0.6 s, then the system might allow the driver to manually override the following gap down to 0.5 s, but once it reached 0.5 s, the system would disallow the driver's continued accelerator pedal override, maintaining the 0.5 s following gap until the driver releases the accelerator pedal.

Regardless of the strategy chosen for accelerator pedal overrides at short following gaps, consideration must also be given to the potential impact on the following trucks. If the driver of a middle truck is currently overriding the CACC gap setting with the accelerator pedal, this would induce an acceleration in the following trucks as they accelerate to maintain their gap setting with their immediately preceding vehicle. A case could be made, in terms of both safety and stability, for the following trucks to ignore the increased gap with the immediately preceding vehicle when it is overriding the CACC system with the accelerator pedal. Essentially, the following trucks would temporarily focus on maintaining the same speed as the string's lead vehicle, rather than focusing on maintaining a constant following gap with the immediately preceding vehicle. After all, the accelerator pedal override should be a temporary state, and would probably indicate that the immediately preceding truck is about to exit the string.

6.3 Data Mismatch Between Forward Sensors and DSRC Messages

A data mismatch between what the forward sensors see (radar or lidar) and what is received by the DSRC communications will occur when an unequipped vehicle cuts into the travel lane. When this happens, the forward sensors should record a change in the forward target and the distance calculated from any DSRC equipped preceding vehicle will not match what the forward sensor reports. This situation could also occur due to GPS errors that place the preceding vehicle out of the travel lane or otherwise distort the measurement. In either case, the C/ACC system should respond by slowly opening the following gap to the shortest available ACC gap setting relative to the closest indicated target, assuming the worst case for safety purposes.

6.4 DSRC Receiving Faults

DSRC communications will fail at times, due to software or hardware failures, channel interference, or line of sight issues. Assuming that CACC messages are transmitted at 10 Hz, a single message or even several messages lost should not adversely affect the operation of the string, unless there also happens to be a hard emergency braking demanded at the same time. If communication is lost for more than 1 to 2 seconds, then the trucks should simply revert to ACC following mode and increase the following gap to the shortest available ACC gap setting while informing the drivers of all following trucks about the nature of the fault.

6.5 Emergency or Hard Braking

An emergency braking, either driver or system initiated could occur for several reasons (cut-in, slowed or stopped vehicle ahead, or debris in the roadway) and be initiated by any of the trucks travelling in the string. Fortunately, with the CACC system active, the braking commands get immediately sent to the following trucks, and if the lead truck initiates the braking, the command gets sent to all following trucks. Since this project is only experimenting with a maximum string length of 3 trucks, any following trucks will always receive the braking command within 100 ms (assuming a 10 Hz DSRC transmission rate), and the CACC systems will be able to start braking faster than even the drivers could react. Additionally, in this project, three identical trucks will be used in the string, and one future research question not covered in this project is how to deal with disparate braking capabilities between trucks during hard braking.

In early ACC systems, the system braking authority was often limited, and during hard braking maneuvers drivers would get an audible and visual alert as the system approached its maximum braking threshold. However, in some later vehicles, the ACC system can be enhanced with or combined with a separate Forward Collision Mitigation Braking System (FCMBS), resulting in a much higher braking authority. On the Volvo trucks that will be used in this project, the ACC system already has full a very high braking authority, so it should be able to respond to any of the anticipated testing conditions. However, the CACC system should also maintain any driver warnings that the standard system would normally give during a hard braking maneuver.

6.6 Stopped Vehicle or Debris in Roadway

Perhaps the most difficult scenario to effectively deal with using CACC is the case when the lead truck in a string or its driver spots a stopped vehicle or debris in the roadway ahead, because the following trucks and drivers in the string will likely be unable to see the hazard given that their forward vision is occluded. If the lead truck driver was not leading a string, then he could simply swerve or change lanes. However, if the lead truck driver executes a lane change, the hazard would be revealed to the following trucks with too little time to react, and even if a quick lane change was possible for the lead truck, it might not be possible for all of the following trucks due to adjacent lane traffic.

Given that the forward vision of the following trucks in a CACC string will be obscured or occluded, the lead truck driver in a CACC string will have some increased responsibility, especially in terms of scanning the roadway and traffic ahead for hazards. In the longer term, the CACC DVI will need to incorporate an ability for the lead truck driver to communicate simple commands or hazardous conditions ahead to the following trucks. For example, if the lead truck driver decides that the CACC string should change lanes, then there needs to be a clear way to communicate that instruction to the following drivers, otherwise, the following drivers won’t know whether the lead truck wishes to continue to be the lead truck, just in a different lane, or wishes to exit the string. For this project, the on-the-road testing will require an additional spotter/radio operator to be seated in the lead truck, and part of that spotter’s responsibility will be to communicate any unexpected hazards or instructions to the drivers of the following trucks over a voice radio link.

7 CONCLUSIONS

While the concept of closely-coupled truck platooning has been the focus of many research projects over the years, it has always included the automation of both lateral and longitudinal control in the following trucks because of the very close following distances targeted by those projects. Cooperative Adaptive Cruise Control (CACC) provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. There are important distinctions between CACC and automated truck platooning. First, with CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, while truck platooning systems have relied on a Constant Distance Gap (CDG) control strategy, CACC has relied on a Constant-Time Gap (CTG) control strategy, where the distance between vehicles is proportional to the speed.

This report mainly focused on describing the various CACC operational concept alternatives, and which alternatives should be employed in this research project. The operational concepts can be broken into four categories: string formation, steady-state cruising, string split maneuvers, and faults or abnormal operating conditions. With CACC string formation, the options included *ad hoc*, local, and global coordination strategies as a means to help the CACC equipped trucks find each other, especially at low market penetrations. Both *ad hoc* and local coordination are appropriate for this project, but global coordination, which includes routing the trucks on city streets, is beyond the scope of this project. The primary issue with steady-state cruising is effectively dealing with cut-ins, which will result in a temporary string split maneuver.

Finally, a number of fault conditions and emergency maneuvers were considered including communication failures, the definition of a kill switch functionality (used in research only), and how to handle obstacles in the roadway and hard braking situations. For the most part, system states, fault conditions, and emergency kill switches must be designed to keep the DSRC broadcast active while attempting to clearly indicate what is happening with the truck since any following trucks will be relying on those transmissions. In the longer term, the role of the CACC string's lead truck driver must be clearly defined when it comes to obstacle detection and avoidance, and the CACC systems will need to incorporate some ability for the lead truck driver to send instructions (lane change) or warnings (road hazards) to the following trucks.

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